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PROJECT GULF Q
A STUDY OF MARITIME CUMULUS MODIFICATION

by

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Research Department

ABSTRACT. Project Gulf Q was conducted 11 through 28 May 1969 at Brownsville, Tex. The objective was to study the modification of warm tropical cumulus clouds by seeding them with hygroscopic solutions that had exhibited considerable warm cloud modification potential. These solutions were sprayed from aircraft on all of the 16 tests completed during the project period. Effects attributable to this treatment were observed in all tests. When cloud growth occurred after seeding, there were frequently marked increases in liquid water content and turbulence, especially in the upper half of the target cloud. On five tests the seeded clouds completely dissipated within 5 to 10 minutes after treatment.

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W. J. Moran, RADM, USN .... Commander
H. G. Wilson .... Technical Director

FOREWORD

The work described in this report is the first in a series of experiments designed to bring about changes in warm cumulus clouds by the addition of hygroscopic agents to such clouds. Work in this country and elsewhere clearly indicates that precipitation from warm clouds may be increased by introduction of particles large enough to begin a coalescence reaction such that the formation of a rain shower may be induced. Further, it seems possible also to greatly modify the form of such clouds by application of hygroscopic materials of different sizes in different parts of the cloud.

The work carried out in these experiments was done by the Naval Weapons Center in May 1969 in collaboration with the Naval Weather Research Facility, Norfolk, Va., and the Atmospheric Sciences Laboratory, White Sands Missile Range. Funding was by AIRTASK A370-5401/216C/OW 3712-0000, Atmospheric Applications, from AIR-540, Naval Air Systems Command.

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INTRODUCTION

STATEMENT OF PROBLEM

The modification of warm cumulus clouds has received considerably less attention than the modification of cold cumulus clouds. As is well known, a triggering mechanism for modification exists in cold cumulus because of the presence of supercooled water drops. Present treatment techniques induce these drops to freeze in a short period of time with a consequent rapid release of heat.

No such triggering mechanism exists for warm cumulus clouds; however, hygroscopic material released rapidly into the cloud in sufficient quantity, and in the right place, could modify a cloud appreciably. Such modification could involve a rapid reduction in humidity caused by the condensation of water on the hygroscopic material and could result in the transport of water from natural cloud drops to the hygroscopic drops. The change in drop size distribution by the introduction of larger drops and the local reduction of small droplets will cause coalescence with other cloud droplets by impact as the larger drops descend. Thus, a precipitation mechanism could be initiated that could result in earlier collapse and dissipation of the clouds.

PROJECT GOALS

The primary goal of Project Gulf Q was to develop techniques using nonfreezing processes that when applied to maritime warm cumulus would enhance the rainfall or cause dissipation of the treated cloud. In support of this goal, in-cloud changes of meteorological parameters were to be measured by aircraft penetrating the treated cloud (see the section on Experimental Techniques). While many studies of this type of cloud have been conducted from ground-based stations (Ref. 1 and 2), much less has been done from aircraft.

A hygroscopic solution used to modify warm fogs during Project Foggy Cloud I at Arcata, Calif., 25 March to 14 November 1968 (Ref. 3) was selected to be tested on warm cumulus in Project Gulf Q. This solution is described in greater detail below.

GENERAL SUMMARY

Brownsville, Tex., was selected as the project site because of the high incidence of maritime warm cumulus clouds over the western Gulf of Mexico at that latitude during the month of May. A series of tests was begun on 12 May 1969; all tests were conducted over the Gulf of Mexico.

In all 16 tests completed during Project Gulf Q, effects attributable to seeding were observed. These included more rapid cloud dissipation than normal, marked increases in liquid water content (LWC) and turbulence, some heavy precipitation, and occasional instances of accelerated cloud growth. The natural lifetime of these clouds is of the order of 20 minutes to one-half hour, and hence natural changes are to be expected to occur within short time periods. The changes noted

TABLE 1. Key Project Personnel.

Project Director	R. Clark, NWC
Assistant Director	W. White, NWC
Data Coordinator	H. Cronin, NWC
Project Meteorologist	MAJ R. Lininger, USAF
Logistics Coordinator	J. Ennis, NWC
Electronics Specialist	G. Bray, NWC
C-47 Commander	LCDR E. Albright, USN, NAF, China Lake
Air Controller	ACC B. Condon, USN, NAF, China Lake
Chief Aircraft Services	O. Bryant, Meteorological Operations, Inc., Hollister, Calif.

herein, however, occurred much more rapidly than in normal cloud processes.

The most interesting test results were observed on five tests in which there was dramatic dissipation of the target clouds. On two of these tests, conducted on different days, the two target clouds were relatively inactive and approximately a mile high and one-half mile wide. After 600 gallons of the hygroscopic solution were dispersed through the emergency dump valves of the seeding aircraft at cloud top, both clouds completely dissipated within 5 to 7 minutes, while adjacent clouds maintained their size. On the other three tests, where the target clouds were in more active growth phases and were associated with a line of cumulus, the solution was sprayed into the top half. After seeding, the cloud growth was arrested almost immediately, and dissipation, beginning at the top, became the dominant process.

PROJECT ORGANIZATION

Project Gulf Q was funded and conducted by the Earth and Planetary Sciences Division, NWC, under the supervision of Dr. Pierre St.-Amand. It was supported by the Naval Air Facility, China Lake; Meteorological Operations, Inc., Hollister, Calif., aircraft services contractor; Southwest Chemical of McAllen, Tex., seeding material contractor; and Weather Science, Inc., Norman, Okla., data reduction.

The U.S. Weather Bureau office at the Brownsville airport provided the project with weather forecasts and supplied climatological data, detailed forecasts, and rawinsonde data. In addition, radar photographs of the test areas were taken by this office at frequent intervals during the operations and furnished to the Project Data Coordinator. Table 1 gives a list of key personnel.

EXPERIMENTAL TECHNIQUES

EQUIPMENT

A Navy C-47 aircraft performed the seeding. Four Cessna aircraft were used to monitor the tests. Two of these were equipped with Minilabs that collected data at the cloud base and at mid-cloud. A third aircraft had two side-looking Mauer aerial cameras for stereophotography. The fourth served as a control-observation aircraft.

The Minilabs in the Cessna 210 aircraft measure (a) altitude, (b) rate of climb, (c) vertical acceleration, (d) temperature, (e) dew point, (f) liquid water content, and (g) rain rate (Ref. 4).

A wing-mounted pod containing sensors feeds signals to a console inside the aircraft where they are amplified and recorded by an 18-channel CEC oscillograph. In addition to the oscillograph, the cloud-base Minilab recorded data on a METRO

DATA DL 620 magnetic tape recorder. These digital tapes were fed through a computer at Weather Science, Inc., to provide tabulations of data from each test.

The primary mission and the principal data gathering equipment of each project aircraft are shown in Table 2.

The C-47 aircraft's spray systems consisted of two internal 500-gallon tanks, spray racks with 86 nozzle stations mounted under the wings, and two externally mounted propeller-driven pumps. Various makes, types, and sizes of spray nozzles can be easily interchanged on this system. The nozzles consisted of standard plastic-bodied disk-type agricultural nozzles with variable core and orifice sizes.

TEST DESIGNS

In order to attack the project goals more systematically, most of the test designs were planned and written before the start of the

TABLE 2. Project Aircraft, Equipment, and Missions.

Aircraft	Special equipment	Mission
Navy C-47	Spray system	Perform seeding assignments
	MRI continuous cloud-particle sampler[a]	Penetrate cloud the specified additional number of passes to make cloud-particle-size determinations
Control aircraft, Cessna 210	16-mm movie camera 35-mm still camera	Operation to be directed from this aircraft by the Project Director via the Air Controller
		Make periodic cloud-top measurements
		Monitor target cloud photographically and visually
Mid-cloud Minilab, Cessna 210	Minilab	Obtain cloud Minilab data at seeding altitude and/or at other specified levels in top half of cloud
Cloud-base Minilab, Cessna 210	Minilab with DL 620 recorder	Obtain cloud base data by making regular cloud penetrations 200 ft above base
		Obtain cloud-base altitude and dimensions
Photo aircraft, Cessna 206	2 Side-mounted 70-mm Mauer aerial cameras	Secure high quality stereo B/W 70-mm photographs of target cloud. Photo runs were spaced so that critical phases of the test were covered
		Supply observation log of test as viewed from a distance of 4 to 7 mi
Photo aircraft, Cessna 205	Documentary camera	Secure documentary footage

[a] Continuous particle sampler failed to function properly because of an erratic pump, and consequently no reliable data were obtained from this source.

project.[1] When necessary, these test designs were modified in order to take advantage of the information learned as the testing progressed.

Since all the tests were conducted over the Gulf of Mexico, a detailed standard airborne observation and data acquisition program was established to document seeding effects. The more important aspects of this program are outlined in Table 2. Data were acquired before and after seeding. The preseed operation usually consisted of two Minilab passes and one photo aircraft data pass to establish natural cloud conditions. The postseed data runs continued for 30 to 60 minutes, after which the test was terminated.

On most tests, the test plan called for the solution to be sprayed into the cloud at a prescribed altitude. In three cases, Tests 10, 11, and 15, however, the solution was deliberately jettisoned at the top of the cloud through the emergency dump valves of the seeding aircraft. This resulted in a rather spectacular dissipation of the target cloud. On Tests 1 through 9, a nozzle with an oval orifice diameter 0.08 by 0.12 inch and a pump pressure of 60 to 80 psi was used. On Tests 12 through 14, and Test 16, a finer spray nozzle with an orifice diameter of 0.047 inch and a pump pressure of 80 to 105 psi was employed. Because all seeding passes were made at constant airspeed, the pump pressures varied inversely with the nozzle orifice diameters.

Some tests were designed to seed the upper half of two types of clouds, one with tops at temperatures below 0°C, the other with tops above 0°C. Tests were also designed to seed the same types of target clouds in updrafts at cloud base. A third series of tests was designed to seed one or more clouds in a line of cumulus to explore the possibility of related growth or dissipation occurring in other clouds in the line.

HYGROSCOPIC TEST SOLUTIONS

The basic hygroscopic test solution had a density of 11.4 lb/gal and was a 9:1 solution composed by weight of 5.14 parts ammonium nitrate, 3.86 parts urea, and 1.00 part of water. The vapor pressure at standard temperature and pressure is 30% of that for water (Ref. 3, Appendix C). This solution was developed for warm fog dissipation tests at Arcata, Calif., during the fall of 1968. As side tests, on two occasions during that project, warm cumulus clouds were seeded with this material (Ref. 3, Appendix D-1). These clouds dissipated rapidly after seeding.

Based on these findings, it was decided to test the seeding effectiveness of such hygroscopic solutions on warm cumulus. The 9:1 solution was used as the seeding agent on Tests 1 through 13. A 12:1 solution was employed on Tests 14 through 16. This more concentrated solution (density 11.5 lb/gal) contained by weight 6.86 parts of ammonium nitrate, 5.14 parts of urea, and 1.00 part of water.

DATA TREATMENT

A preliminary, rapid evaluation and review of all data logs, photographs, weather charts, etc., for each test was conducted by the Project Data Coordinator. A test summary log, compiled so that important test facts could be studied with a minimum of effort and time, was particularly valuable in modifying test designs. A more detailed review of the data was made at NWC after the termination of the project by a two-man data-analysis team. This team ascertained whether or not the collected data confirmed the visual observations made by the test participants. A detailed data analysis was not warranted since the purpose of the project was to make a preliminary investigation of the effects of the hygroscopic solution on warm cumulus. Because of the rather dramatic test results observed at Brownsville, this data review will materially aid in designing a more comprehensive series of tests for a future project.

[1] Naval Weapons Center. "Gulf 'Q,' Phase I OP Plan 1-69," by the Earth and Planetary Sciences Division, China Lake, Calif., NWC, May 1969.

DISCUSSION

The test results are summarized in Table 3. Effects that could be attributed to seeding were observed on all the tests. When the cloud grew after seeding, the generally light-to-moderate turbulence observed on the preseed passes by the upper Minilab aircraft changed to moderate to severe. On several occasions the increase in turbulence occurred within 1 to 3 minutes after the initiation of seeding. This was observed by both Minilab aircraft on penetrations between seeding runs and by the seeder aircraft on its second pass through the cloud. Also, immediate increases in LWC and precipitation were noted by each of these aircraft.

TABLE 3. Gulf Q Test Summary.

Test no.	Date, 1969	Time (CDT)		Objective	Hygroscopic solution		Nozzle type	Seeding placement in cloud, ft, MSL	Remarks
		Begin seeding	End test		Type	Amount, gal			
1	12 May	1520	1552	Test techniques and systems; develop precipitation below freezing level	9:1	500	2515	Top half, at 7,500 ft.	LWC and turbulence in top half of cloud increased markedly immediately after seeding
2	14 May	1144	1210	Increase precipitation below seeding altitude	9:1	700	2515	Top half, at 4,500 ft	Target was poor since it was located in a mass of clouds and had an excessive base-to-height ratio. Slight increase in LWC and turbulence on top half. Very light sporadic precipitation at base
3	16 May	1127	1157	Dissipate warm cumulus by seeding in top half	9:1	600	2515	Top half, at 7,200 ft	Clouds in area were growing. After seeding, cloud top flattened. Turbulence and LWC increased throughout cloud. Precipitation from cloud base increased after seed. Target was in a mass of clouds and became difficult to identify
4	19 May	1138	1158	Seed a line of small cumulus to promote merging growth	9:1	600	2515	Top half, at 6,500 ft	Seeded a single cloud since a line of cumulus was not available. Turbulence and LWC remained at preseed levels until about fifth postseed Minilab pass when they began to decrease as target cloud began to dissipate
5	21 May	1630	1700	Suppress cloud growth along a section of a line of cumulus	9:1	600	2515	Top half, at 4,600 ft	LWC began decreasing after seeding. Two tops dissipated. Most active turret top fell 600 ft. Funnel developed along seed trail. No precipitation at base

TABLE 3. (Contd.)

Test no.	Date, 1969	Time (CDT) Begin seeding	Time (CDT) End test	Objective	Hygroscopic solution Type	Hygroscopic solution Amount, gal	Nozzle type	Seeding placement in cloud, ft, MSL	Remarks
6	22 May	1055	1136	Seed in base of warm cumulus to instigate growth	9:1	600	2515	Approx. 2,000 ft above base at 4,500 ft in updraft	Seeded large cumulus. Moderate to heavy rain at cloud base before and after seeding. Rapid growth and dissipation cycles (8-min periods) were evident after seeding
7	23 May	0936	1010	Seed in thin dry layer between two active moist air layers to grow clouds through inversion	9:1	600	2515	Along tops at lower clouds in clear air, 9,000 ft	Lower clouds developed along seed line but tops did not break through inversion. Seed material hung in air for several minutes after seeding
8	23 May	1233	1320	Second attempt to break through dry layer by seeding in top half of lower clouds	9:1	600	2515	Top half of single cloud, at 7,900 ft	Objective was abandoned since upper clouds had dissipated naturally. Immediately after seeding, cloud began rapid cycling process. Associated increases in turbulence and in-cloud LWC were very dramatic. Only light precipitation at base
9	23 May	1555	1639	Enhance growth rate of a warm cumulus by seeding in cloud base	9:1	600	2515	In updraft about 3,000 ft above base; tops 12,000 ft	After seeding, cloud exhibited immediate pronounced vertical development and rapid cycling. Adjacent clouds were not so active. Base rainfall increased from light to moderate/heavy after seeding. Penetrating Minilab aircraft curtailed passes because of severe turbulence after seeding (2,000 ft/min updraft)
10	24 May	1131	1144	Dissipate warm cumulus by dumping load in top of cloud	9:1	600	Two dump valves (45 sec per 300 gal tank)	Two dump passes in cloud top, at 8,500 ft	Cloud dissipated within 5 min after first seeding pass. Cloud was not growing before seeding. Very dramatic effect; adjacent clouds exhibiting periodic growth and dissipation cycles
11	25 May	1110	1125	Dissipate growing cumulus by dumping load in top of cloud	9:1	600	Dump, see Test 10	Load dumped at top in 2,000 ft/min downdraft	Very dramatic dissipation effect. Cloud gone within 10 min. Dissipation time longer than for Test 10 because cloud was larger and growing. Hole developed through center of cloud. Cloud collapsed inward

TABLE 3. (Contd.)

Test no.	Date, 1969	Time (CDT)		Objective	Hygroscopic solution		Nozzle type	Seeding placement in cloud, ft, MSL	Remarks
		Begin seeding	End test		Type	Amount, gal			
12	26 May	1028	1105	Enhance cloud growth by seeding in base updraft	9:1	300[a]	D3/25	Near mid-cloud, at 5,000 ft	Objective changed to top half seeding to enhance growth. New finer spray nozzle used; 60 gal/min spray rate. Definite funnel observed along seed track and 2,000 ft below. LWC and turbulence increased immediately after seeding but dropped off as cloud began dissipating slowly
13	26 May	1622	1648	Dissipate warm cumulus by seeding at top	9:1	600	D3/25	Top, at 4,500 ft	Seeded several tops in a line. Tops in this line began to dissipate after seeding. Target was not growing at seed time
14	27 May	0942	1027	Seed warm air cumulus to develop growth of cloud through freezing level	12:1	575	D3/25	Top half, at 7,000 ft	First test using 12:1 solution. Cloud appeared to have stopped growing prior to seeding. After seeding, considerable vertical growth began with rapid cycling developing during postseed period. Target regenerated by seeding
15	27 May	1423	1447	Dissipate warm cumulus by dumping load at top	12:1	575	Dump, see Tests 10 and 11	Load dumped at top, at 8,200 ft	After dump, cloud began to dissipate steadily and was gone in 10 to 12 min. Target cloud was similar to the one in Test 11. The 12:1 solution dump differed very little from the 9:1 solution dump of Test 11
16	28 May	0827	0903	Dissipate or grow warm cumulus by seeding in top half of cloud	12:1	575	D3/25	Two targets, top half at 7,000 ft	First cloud dissipated in 8 min after 3 seeding passes. Second target was adjacent to first but was considerably more active with heavy rain and severe turbulence. Seeded portion of second target dissipated in 10 to 15 min

[a] Mechanical problems to aircraft prevented full 600-gallon seeding.

When dissipation occurred, it was rapid. Usually, the cloud had reached its maximum growth. However, even if it had begun to dissipate naturally, the rate increased markedly. Figure 1 illustrates a case of dissipation (Test 11) within 9 minutes after a cloud had been seeded by having the solution dumped into it at 8,500 feet. The morning sounding at Brownsville is shown in Fig. 2. Although Test 11 was conducted 4 hours later, the Minilab temperature data indicate that conditions above altitudes from 2,000 to 3,000 feet were similar to those at the time of the sounding. In the photographs a level of weakness in the cloud is seen in the region of the inversion and dry layer at 4,500 feet. The inversion and drying at 8,000 feet limited cloud growth to about 9,000 feet.

The preseed and the first postseed passes by the one Minilab aircraft on this test are shown in Fig. 3. Both penetrations were made at approximately 6,200 feet. Times of the passes were 5 minutes preseed and 3 minutes postseed. The most striking change occurring between the two passes was the marked reduction in LWC from a peak of over 2.0 g/m^3 to 0.3 g/m^3.

The rather dramatic and rapid changes of a growth case (Test 14) are illustrated in Fig. 4. A photograph of the cloud taken by the photo aircraft is accompanied by a corresponding graph of Minilab data at mid-cloud penetration. The target was a turret growing from a cloud mass of stratus and stratocumulus. Note the direct correlation between the vertical extent of the cloud and the LWC. The height of the cloud top, as measured by the control aircraft, and the LWC are plotted against time in Fig. 5.

Apparently, the first preseed pass was made just after the target cloud began to dissipate. Seeding occurred just before the cloud became almost indistinguishable from the general cloud mass. About 10 minutes later the turret began to build again. Twenty minutes after seeding it began to cycle rapidly, with six distinguishable cycles occurring in the next 45 minutes. The last five cycles averaged 7 minutes apart. During this period, the altitude of the cloud top varied by

(a) At seed.

FIG. 1. Dissipating Warm Cumulus. Test 11, 25 May 1969.

NOT REPRODUCIBLE

(b) Four minutes after seed.

(c) Nine minutes after seed.

FIG. 1. (Contd.)

2,000 feet or more and the amount of the LWC by as much as 3 g/m^3.

Only light precipitation was noted by the cloud-base Minilab aircraft throughout the test. The observer in the mid-cloud aircraft noted no precipitation until pass 9, 25 minutes after seeding. Analysis of data from the rain-rate meter (Ref. 5) yielded a rainwater content of 0.03 g/m^3. The rainwater content was 0.67 g/m^3 on pass 13, about 6 minutes later. Thereafter, it decreased until the end of the test. By comparison, maximum LWC (4.2 g/m^3) occurred 30 minutes after seeding on pass 11.

The data were examined to determine whether there were any temperature changes attributable to seeding. Figure 6 shows the temperature data from the mid-cloud aircraft for climbout from Brownsville. Temperature and dew point from the morning Brownsville sounding are also shown. Although the aircraft data indicate somewhat warmer temperatures as might be expected, the differences are only about 1 degree from 5,000 to 8,000 feet. Temperature data for clear air adjacent to the cloud are also plotted. These seem slightly lower and fall on the sounding curve. Unfortunately, the aircraft used to gather these data had no dew point sensor.

Temperature and dew point data are plotted for the cloud-base aircraft in Fig. 7. The moisture on ascent can be accounted for by the fact that the ascent was over land and the aircraft was at maximum altitude at the coastline. At this time, there were stratocumulus and small cumulus clouds along the coast. En route to the target, the data show the dry layer beginning at 5,000 feet. While the temperature decreased slightly during the descent to penetration altitude on approach to the target cloud, the dew point lowered by about 4°C. During cloud penetrations, the temperature-dew point spread was much less.

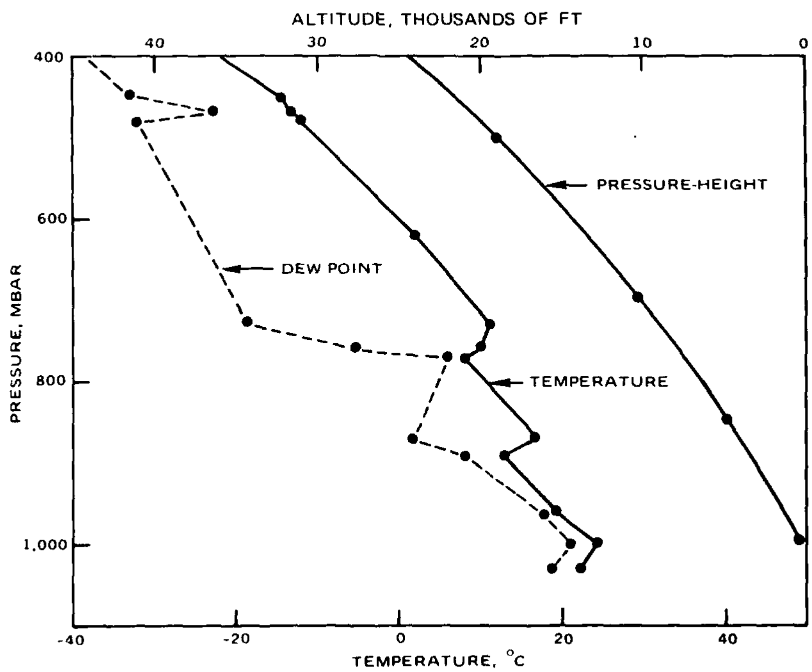
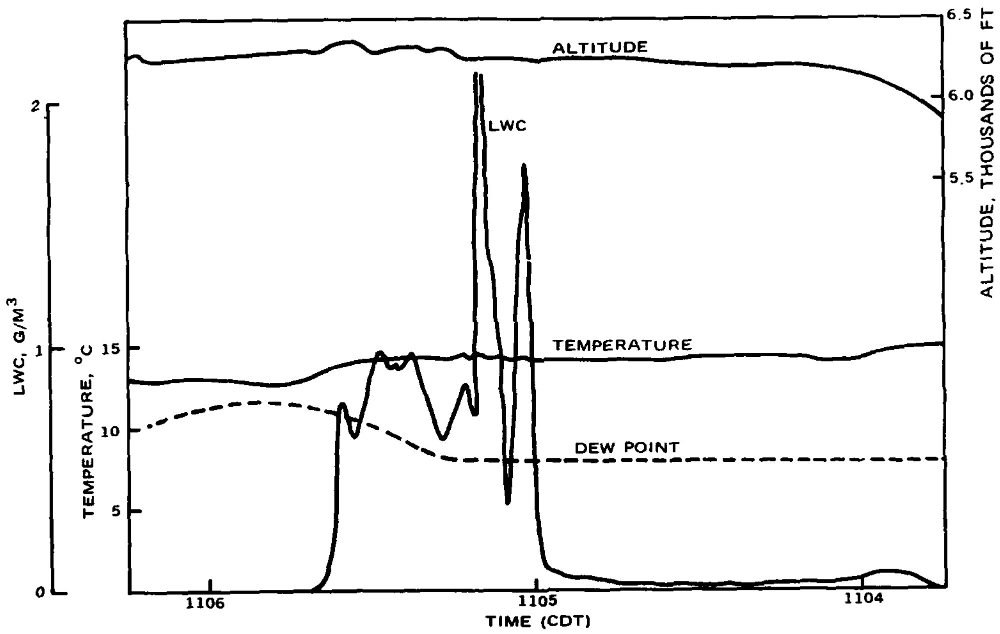
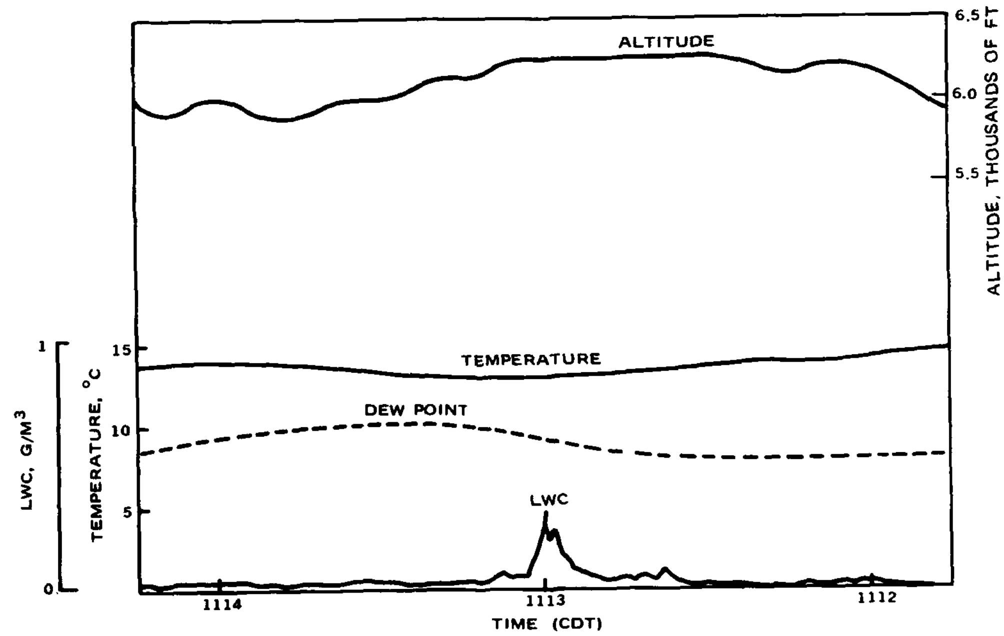


FIG. 2. Brownsville Sounding at 0700 CDT, 25 May 1969, Showing Temperature, Dew Point, and Pressure-Height Curve Versus Pressure.



(a) Preseed at 1105 CDT. Compass heading: 300 degrees.



(b) Postseed at 1113 CDT. Compass heading: 120 degrees.

FIG. 3. Liquid Water Content, Temperature, Dew Point, and Altitude, From Cloud Penetrations Versus Time. Increasing time from right to left. Test 11, 25 May 1969. Seed at 1110 CDT.

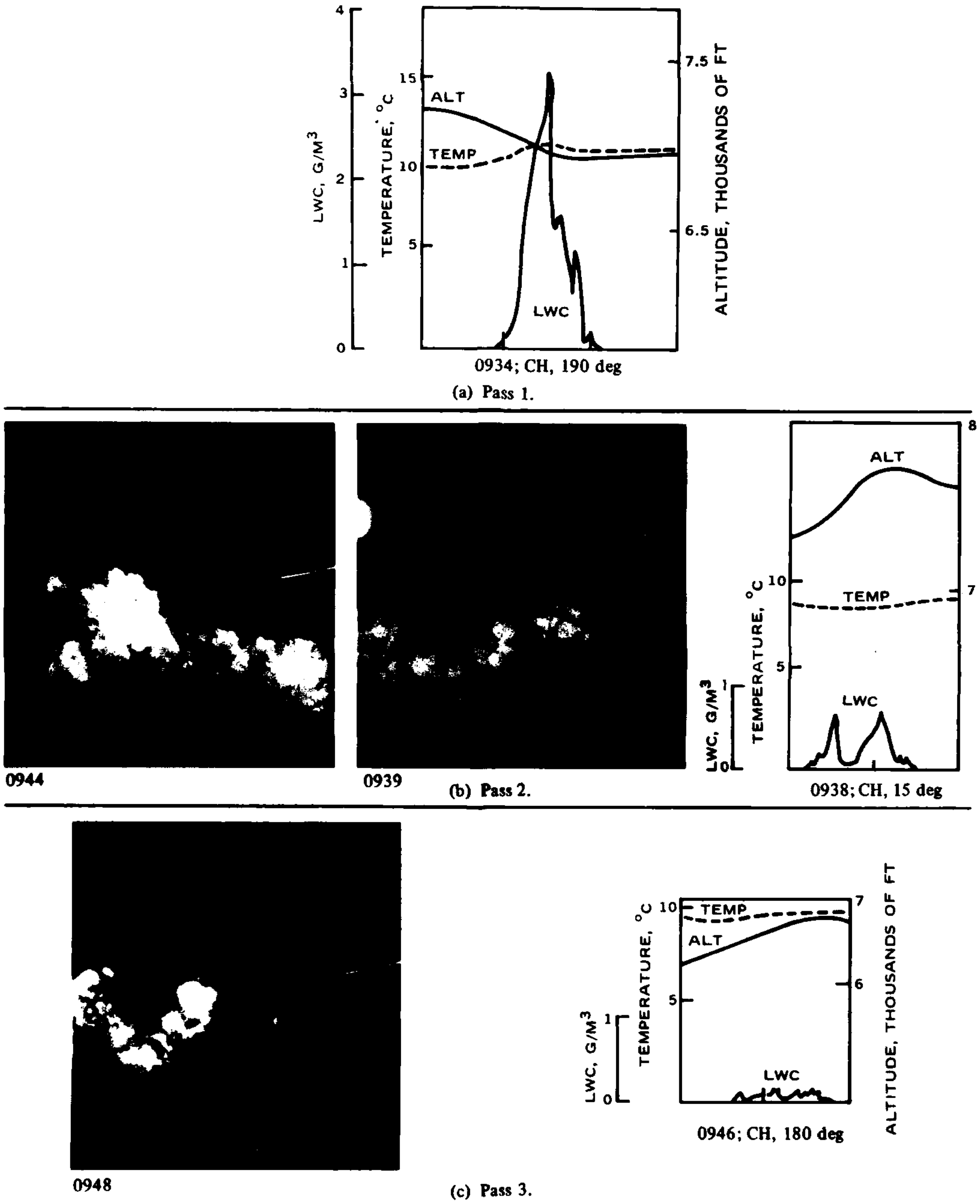
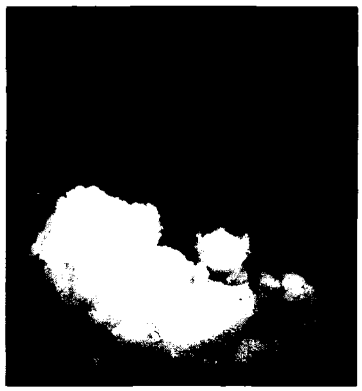
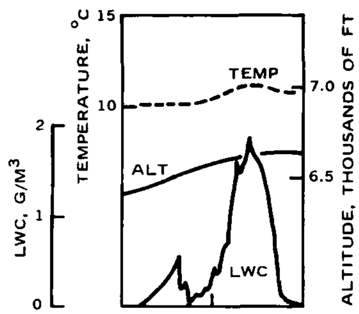


FIG. 4. Liquid Water Content, Temperature, and Altitude Versus Time. Increasing time from right to left. Test 14, 27 May 1969. See Table 3 for explanatory data. Photos from passes 2-7 were taken from approximately 4 nmi; photos from passes 8-15 from approximately 7 nmi. Compass heading (CH) applies to graphs only.

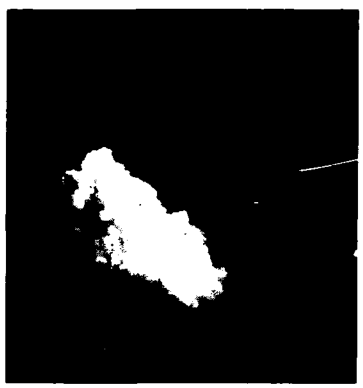


0952

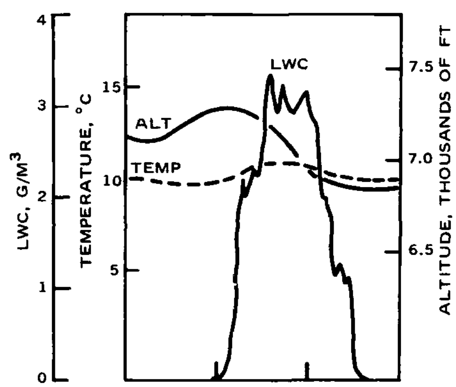


0950; CH, 180 deg

(d) Pass 4.

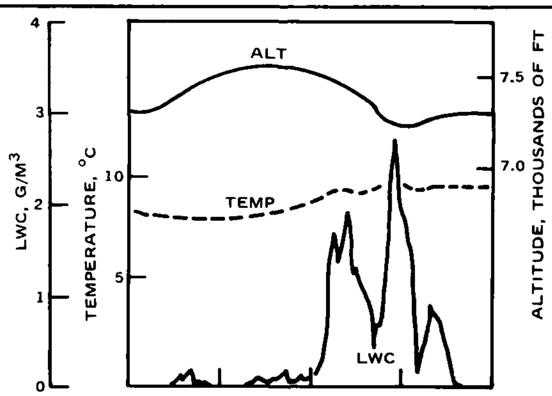


0956



(e) Pass 5.

0953; CH, 12 deg

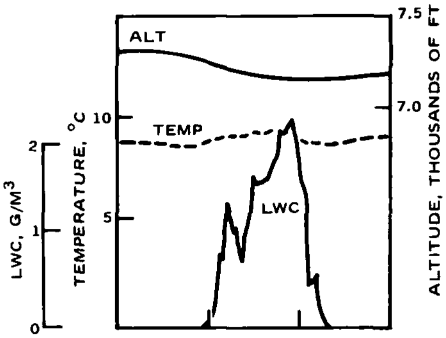


0956; CH, 183 deg

(f) Pass 6.

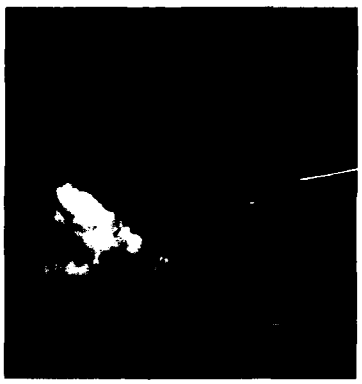
FIG. 4. (Contd.)

1000

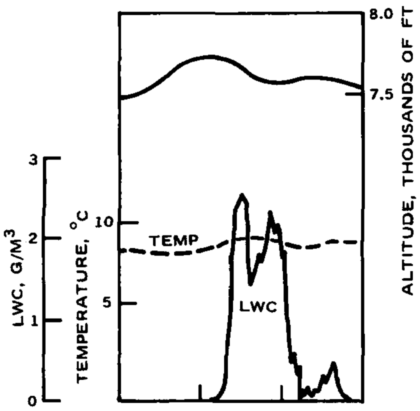


0959; CH, 4 deg

(g) Pass 7.



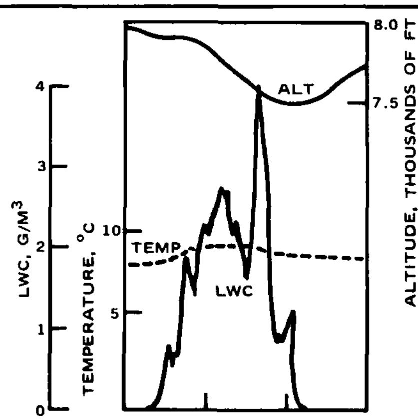
1003



(h) Pass 8.

1002; CH, 182 deg

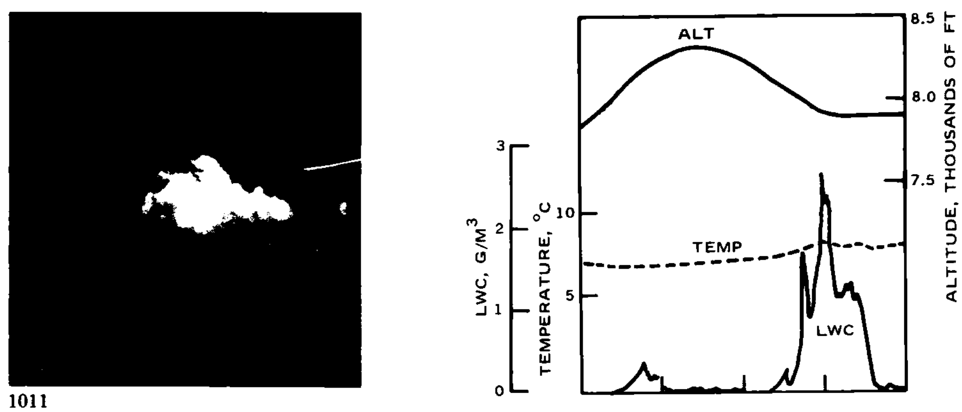
1007



(i) Pass 9.

1005; CH, 335 deg

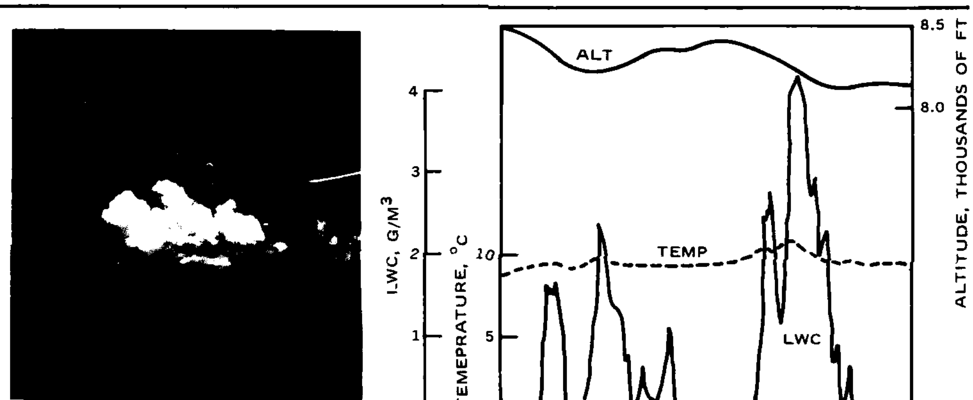
FIG. 4. (Contd.)



1011

1008; CH, 180 deg

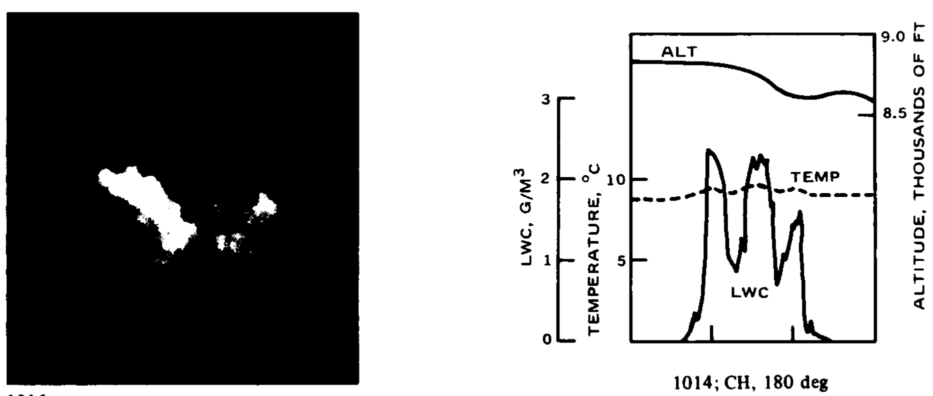
(j) Pass 10.



1012

(k) Pass 11.

1011; CH, 345 deg

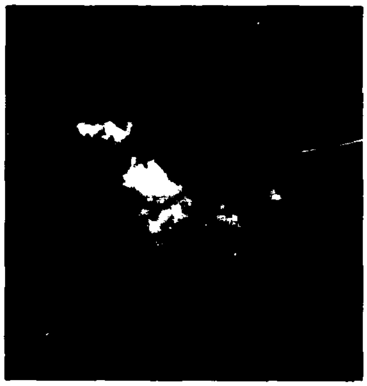


1016

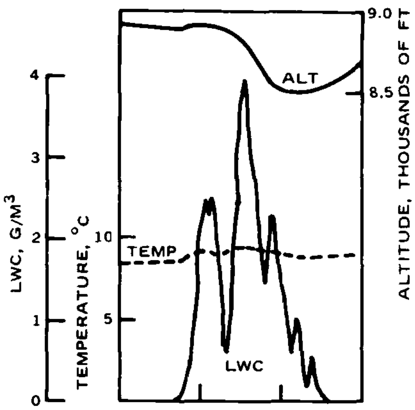
1014; CH, 180 deg

(l) Pass 12.

FIG. 4. (Contd.)



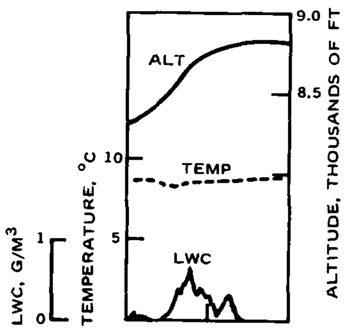
1018



1017; CH, 340 deg

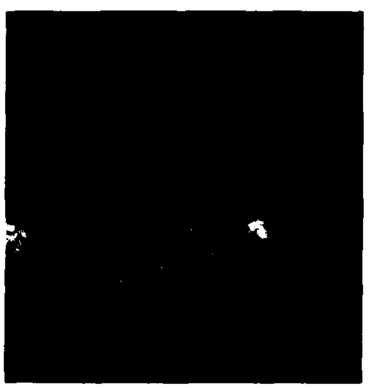
(m) Pass 13.

1024

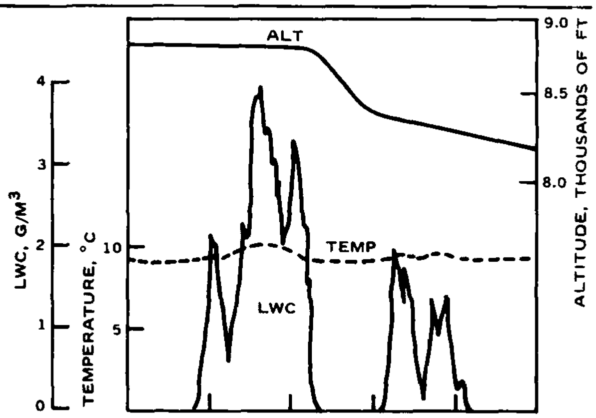


1020; CH, 150 deg

(n) Pass 14.



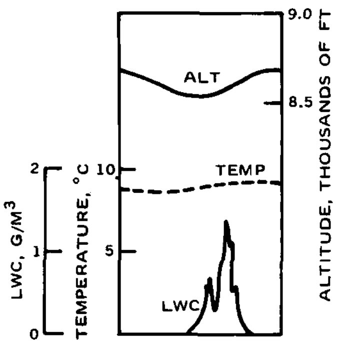
1025



(o) Pass 15.

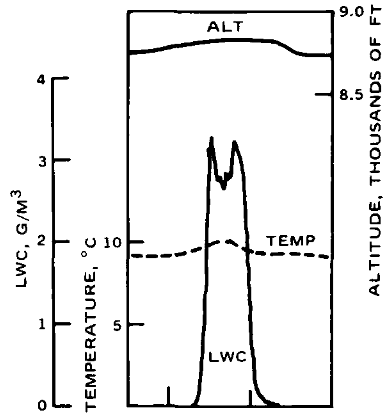
1024; CH, 340 deg

FIG. 4. (Contd.)



1026; CH, 172 deg

(p) Pass 16.



1028; CH, 342 deg

(q) Pass 17.

FIG. 4. (Contd.)

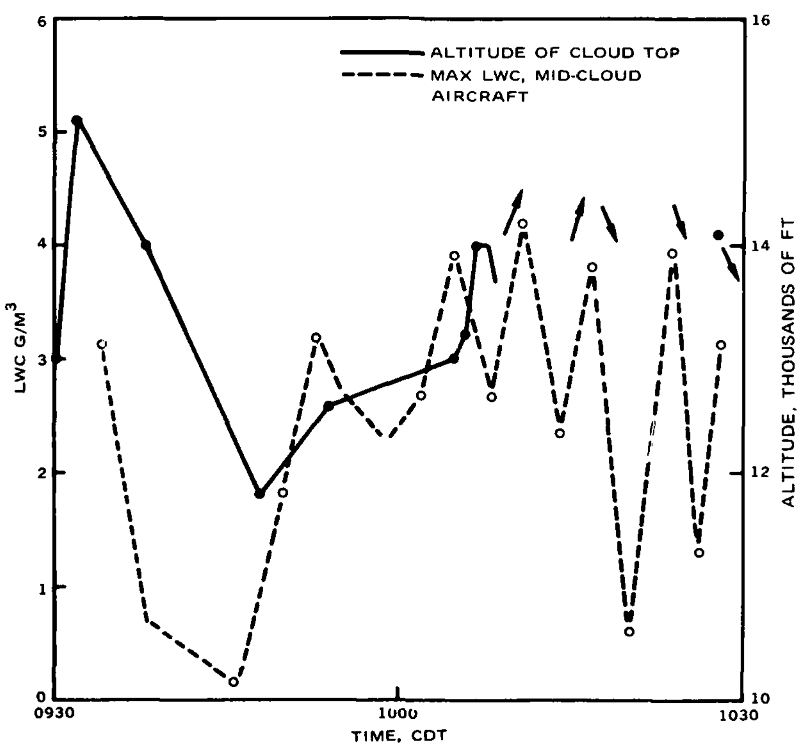


FIG. 5. Maximum Liquid Water Content per Pass and Cloud-Top Altitudes Versus Time. Test 14, 27 May 1969. From 1008 to end of test, arrows indicate direction of growth of cloud based on observer's comments.

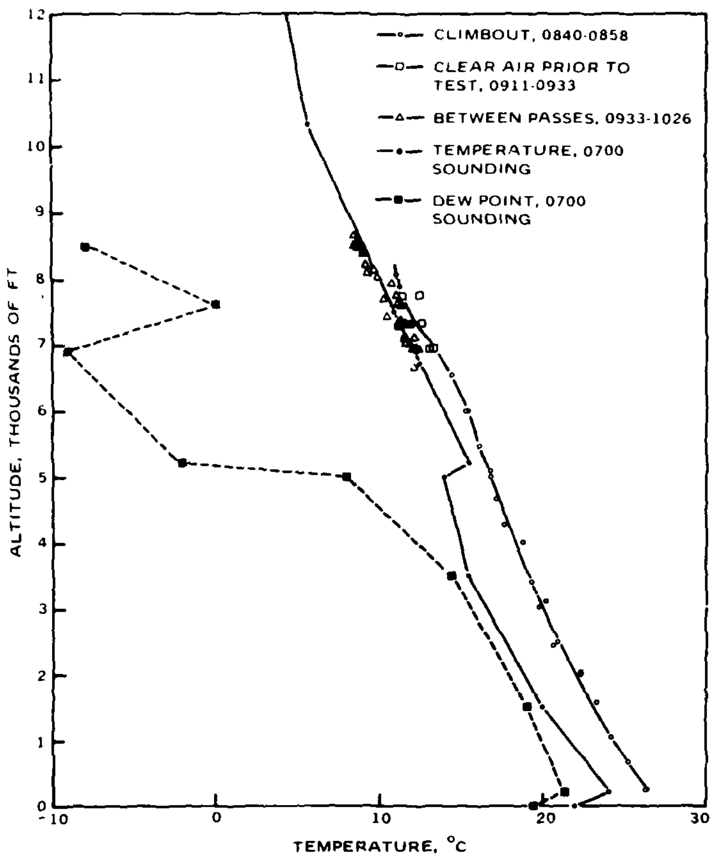


FIG. 6. Temperature and Dew Point Versus Altitude. Test 14, 27 May 1969. Data from 0700 CDT Brownsville sounding and mid-cloud aircraft.

The only temperature changes of note were those in the area of maximum LWC. This is shown in Fig. 8, where the in-cloud temperature rise is plotted against maximum LWC. As Fig. 4 showed, the maximum change in temperature is well correlated with the LWC peaks. Within the scatter of the data, the LWC-versus-temperature rise is linear. No similar plot is shown for the cloud-base aircraft because the LWC was very low and reached only a few tenths of a gram per *cubic meter*.

Conditions portrayed by the Brownsville weather radar are summarized in Table 4 for certain tests selected as representative of Project Gulf Q.[2] The data from these tests were examined in detail to assist in planning a follow-on project. Although penetration aircraft on both Tests 11 and 14 noted light precipitation, it was not heavy enough to show on the weather radar.

Although Test 14 exhibited a rapid cycling of growth and dissipation, it did not show the typical increase in turbulence and LWC of a

[2] Radar photographs were analyzed by Weather Science, Inc., Norman, Okla.

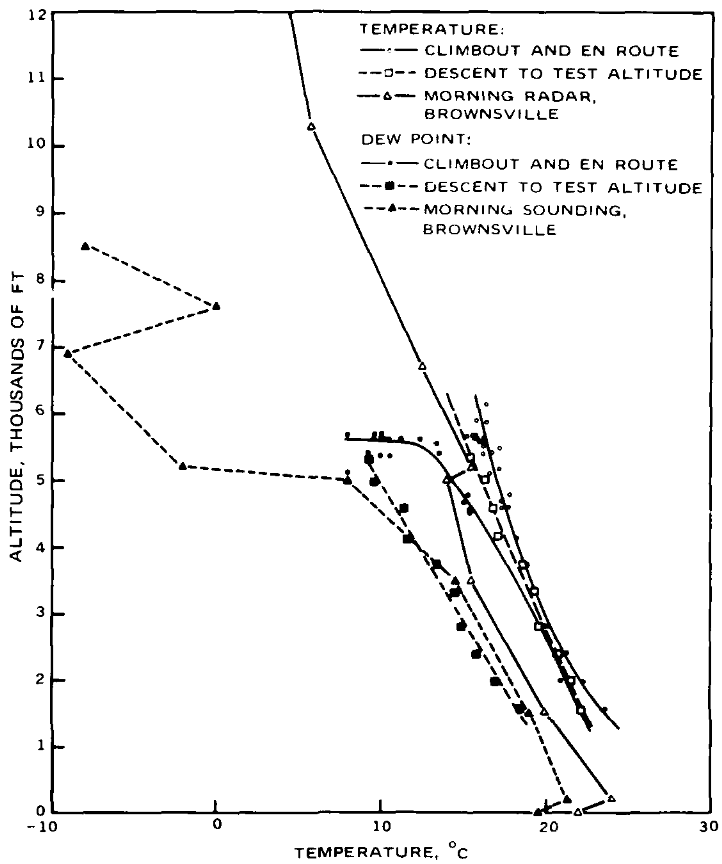


FIG. 7. Temperature and Dew Point Versus Altitude. Test 14, 27 May 1969. Data from 0700 CDT Brownsville sounding and cloud-base aircraft.

growing cloud after seeding as did Test 9.

Data from a preseer pass and first postseed pass by the mid-cloud aircraft are shown in Fig. 9. Pilots were instructed to maintain the aircraft at constant attitude and power setting and at an indicated airspeed of 100 knots while penetrating clouds. The aircraft would then change altitude with up- and downdrafts, and hence a measure of cloud turbulence could be determined from the rate-of-climb indicator. Unfortunately, the rate-of-climb electronics malfunctioned, and this parameter was not recorded on the CEC recorder chart.

The altitude trace, however, indicates that the aircraft encountered a general downdraft area in the cloud on the preseed pass. The first postseed pas was made 2 minutes after the first of two seed passes. Note the sharp increase in altitude about mid-pass, indicating a strong updraft. The peak value of LWC doubled, and the entire LWC trace indicates that there was roughly three times the condensed water in the cloud at the penetration altitude. Approximately 15 minutes after seeding, in-cloud turbulence became so severe that this mid-cloud aircraft had to stand clear of the cloud for 12 minutes.

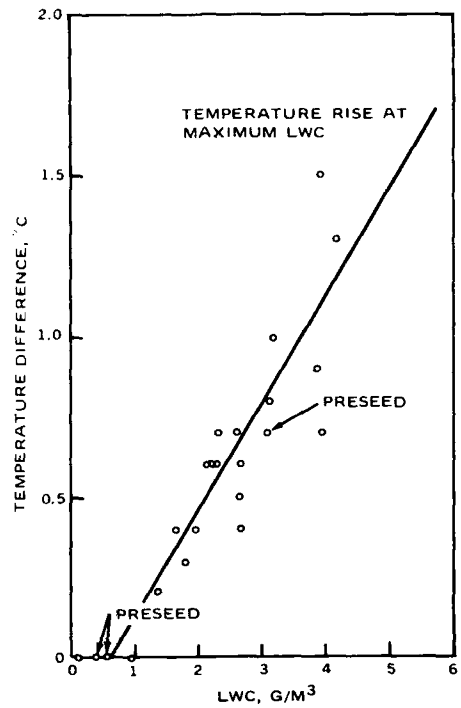
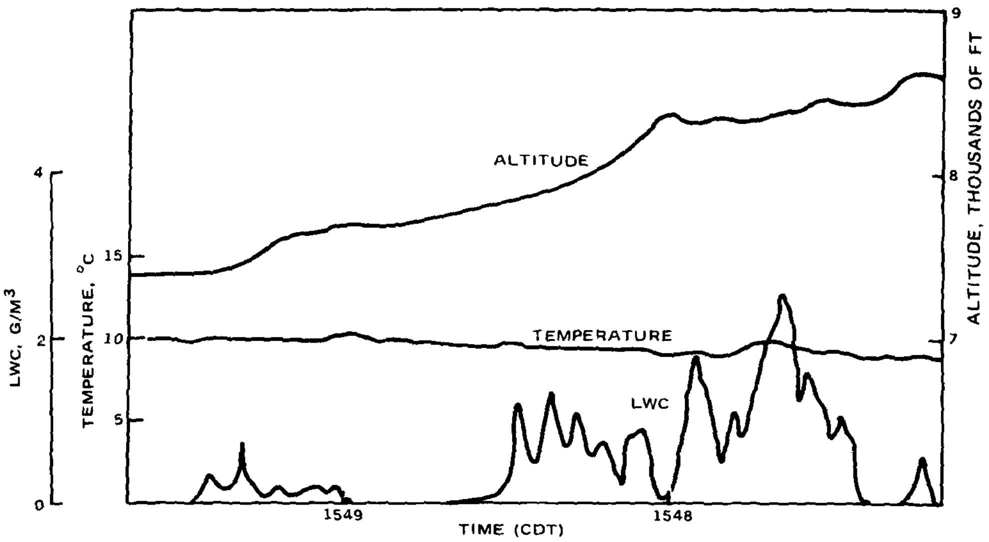


FIG. 8. In-Cloud Temperature Rise Versus Maximum Liquid Water Content. Test 14, 27 May 1969.

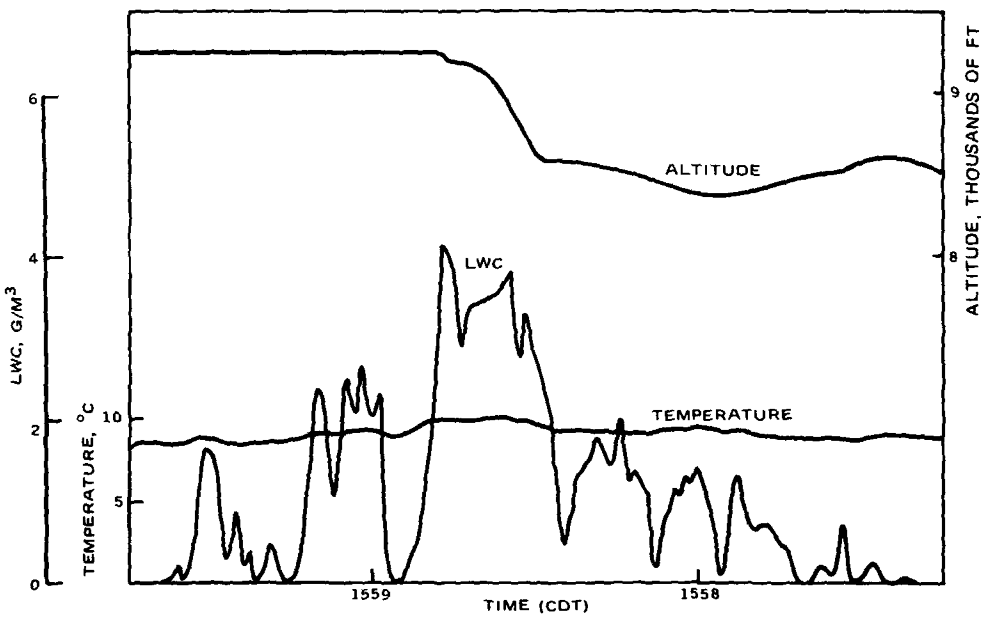
TABLE 4. Weather Radar Analysis, Brownsville, Tex., 1969.

Radar was in long pulse mode.

Test no.	Echoes before seeding	Seeding-produced echoes	Time echoes lasted, GMT	Other echoes in area	Remarks
9	yes	yes	2055–2208	no	Target cloud had 2 small areas of precipitation
10	no	no	. . .	no	Radar painted aircraft in target area
11	no	no	. . .	yes	3 areas 25 to 30 mi SE intensified approx. 20 min after seeding. Intensified for approx. 1 hr
12	yes	no	. . .	yes	3 small areas of precipitation before seeding. Precipitation disappeared during seeding. Too close to ground clutter for effective analysis
14	yes	no	. . .	yes	Precipitation areas 20 and 45 mi farther out. Radar painting aircraft in target area
16	yes	yes	1339-unknown	yes	Seeding accomplished in an open space in a line of precipitation NW-SE. Precipitation joined line



(a) 7 minutes prior to seed. Compass heading: 005 degrees.



(b) 3 minutes after beginning seeding. Compass heading: 150 degrees.

FIG. 9. Data From Mid-Cloud Penetration by the Minilab Aircraft, Test 9, 23 May 1969.

This cloud also exhibited growth and dissipation cycles, illustrated in Fig. 10. Again, there is a marked correlation between the height of the cloud top and the values of maximum LWC. The cloud finally dissipated about 45 minutes after seeding began.

The cloud-base aircraft's data system was modified to record sensor outputs on tape. These data were analyzed and plotted by computer by WSI, Norman, Okla. A sample is shown in Fig. 11 for Test 14.

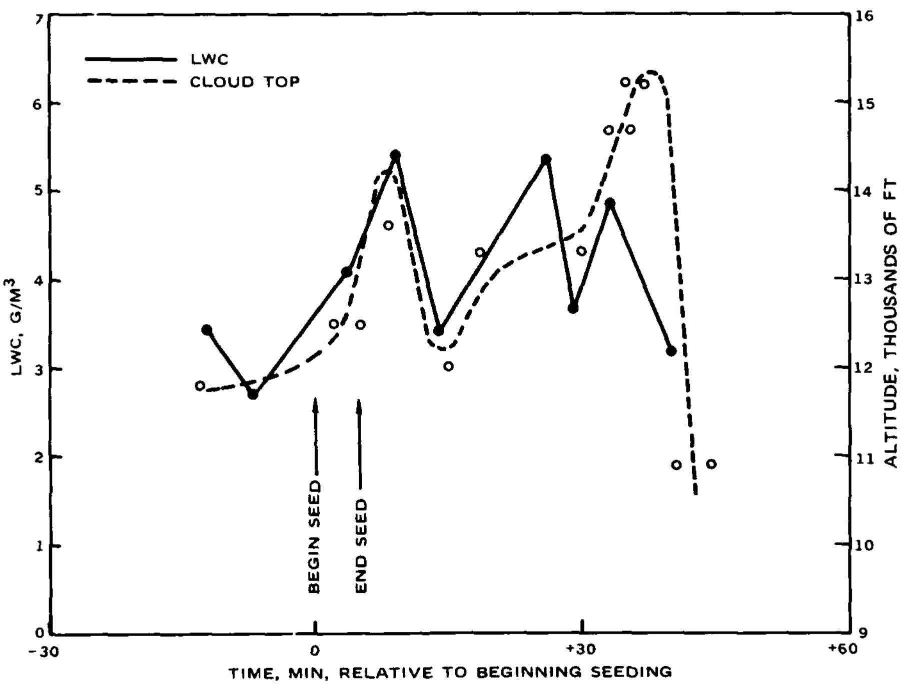


FIG. 10. Correlation of Maximum Liquid Water Content With Cloud Top Altitude. Test 9, 23 May 1969.

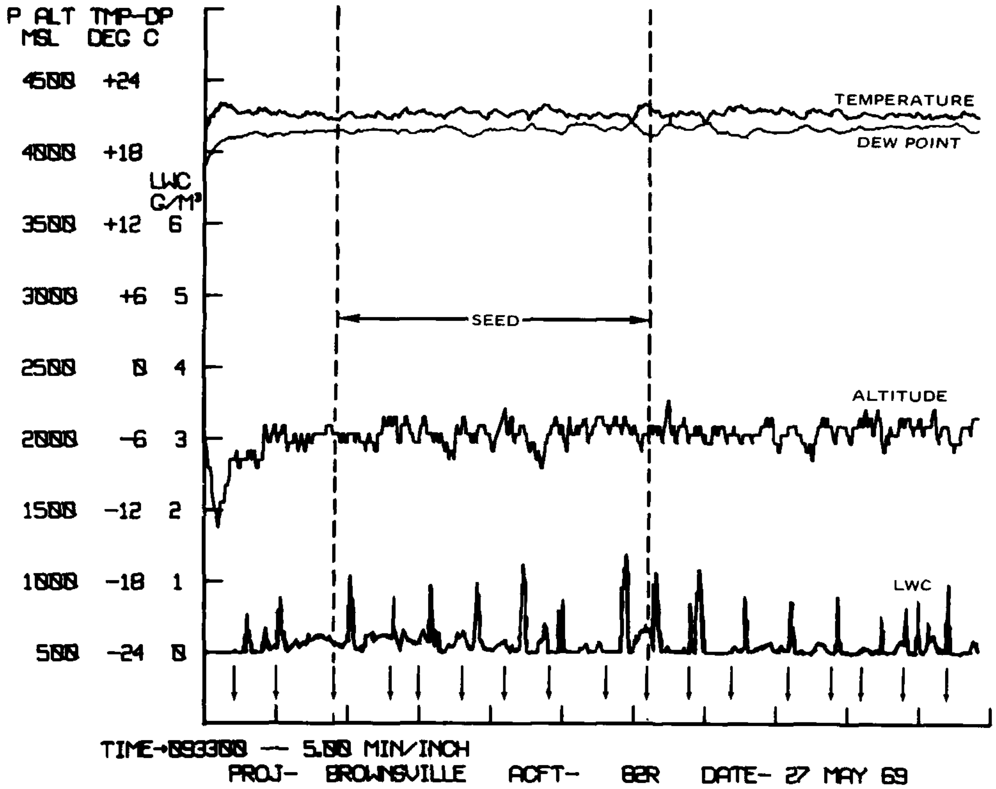


FIG. 11. Computer Plot of Liquid Water Content, Temperature, Dew Point, and Altitude Versus Time. Test 14, 27 May 1969. Arrows denote times of initial cloud penetration. Liquid water content as portrayed is three times greater than actual because of computer programming requirements.

CONCLUSIONS AND RECOMMENDATIONS

From the series of 16 field tests on Project Gulf Q at Brownsville, Tex., in May 1969, it was concluded that warm cumulus clouds were significantly modified by the hygroscopic solutions of ammonium nitrate and urea. Such modification was often dramatic. Depending upon cloud size and growth stage, either dissipative or growth effects could be achieved by dumping or spraying the solution into the cloud. It was decided that in order to expand upon these results, a second project should be scheduled. The ultimate goal of this series of projects will be to fully develop operational techniques for modifying any type of warm cumulus. These operational techniques could be perfected to meet both military needs and civilian applications.

Listed below are some recommendations concerning test objectives and operational techniques for warm cumulus projects.

1. Reliable criteria should be established for predicting whether a given warm cumulus will dissipate or grow when seeded with the hygroscopic solution. To achieve this objective, it is important to understand the natural life cycle of warm cumulus under a variety of temperature and moisture conditions. It is recommended that for future tests a Minilab aircraft and appropriate personnel be dispatched to the operations area one week prior to scheduling testing in order to make this study.

2. An attempt should be made to maximize seeding effects and determine the minimum amount of solution needed to achieve these effects. A determination of the best altitude within the cloud at which to seed, optimum particle sizes, and most effective spray rates should also be made in order to maximize seeding effects.

3. It is suggested that the next project also be conducted at Brownsville. Warm cumulus cloud test conditions exist in this area several months of the year. In addition, this area furnishes the project excellent agency and logistical support.

4. A mobile radar installation should be set up near the Brazos Santiago radio beacon on Padre Island where the radar would be within monitoring range of all operations. From this installation the air controller can monitor the plan position indicator scope, vector the project aircraft during operations, and furnish the needed aircraft and target-cloud positional information. A portable weather radar system and APT (automatic picture transmission) weather-satellite cloud-picture receiver should be located at the radar site. A receiver and other related equipment capable of monitoring dropsonde signals should be installed so that weather parameters from the actual testing site can be obtained. Copies of the sounding data made at the Brownsville weather office should still be acquired for use as background data for environmental comparison studies.

5. Investigators concerned with numerical cloud modeling should be consulted in designing the cloud treatment experiments. The utility of modeling has been demonstrated by Nelson (Ref. 6) in analyzing the results of water-spray seeding tests conducted by Braham, Battan, and Byers (Ref. 7). Nelson used Berry's theoretical work (Ref. 8 and 9) on growth of precipitation-sized particles from an original spectrum of small drops. He was able to show that although peak rain intensity and total rainout were less, the onset of rain occurred earlier than under natural conditions.

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13. ABSTRACT

Project Gulf Q was conducted 11 through 28 May 1969 at Brownsville, Tex. The objective was to study the modification of warm tropical cumulus clouds by seeding them with hygroscopic solutions that had exhibited considerable warm cloud modification potential. These solutions were sprayed from aircraft on all of the 16 tests completed during the project period. Effects attributable to this treatment were observed in all tests. When cloud growth occurred after seeding, there were frequently marked increases in liquid water content and turbulence, especially in the upper half of the target cloud. On five tests the seeded clouds completely dissipated within 5 to 10 minutes after treatment.